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Abstract: High temperature superconductors (HTS) enable very compact electric machines with high power density. Here, an HTS power generator based on authors' previous double claw pole design is studied and improved. The original design of the double claw pole machine features a stationary field core to provide support and access to the superconducting field winding and its cryostat. It does not serve any other purpose. However, a homopolar field passes through it. The improvement was made to replace the field core by iron-cored copper coils, creating an inner stator within the generator to increase the electric loading. Through this step, the power output of the generator was increased from 10 to 11.6 MW, increasing the power density from 54.28 to 63.54 W/kg while maintaining the same outer diameter.

1 Objectives and context

One of the biggest challenges the wind energy sector faces is to reduce the cost of energy. For several decades, now there has been a trend towards higher power-rated wind turbines [1], which help reduce the cost of energy through lower installation and maintenance costs per kilo-watt hour. However, one critical issue with large wind turbines is the tower head mass problem. The tower head becomes extremely heavy for large wind turbines; this leads to a need for more robust foundation towers for support which in turn dramatically increase the cost of the whole system [2]. To solve this issue, a novel lighter topology of power generators based on superconductor technology is required which would enable 10 MW and even higher rated wind turbines. With this objective, the double claw pole machine was designed. It is a 10 MW, 10 rpm superconducting generator. Referring to [3], the main advantages and the concept of the double claw pole machine can be described as follows. It is an axial flux machine. Claw poles are oriented around the superconducting field winding. These are oriented in an alternating fashion creating a North-South pole flux variation across the stator teeth. A stationary field core is required in between the small claw poles in order to support the superconducting winding and its cryostat. The stationary field winding eliminates the need for cryocouplers and brushes operating the superconducting winding with a DC current ensures that there are no AC losses present. The double claw pole machine only uses a small amount of superconducting tape due to the iron-cored design and the loop-shaped field winding. At 30 K, the design only requires 3.4 km of YBCO tape and for 65 K, it requires 13.5 km. In addition, the machine is highly modular, the two stator sides can operate independently from each other in case of a fault. The field winding can be wound into separate loops with separate cryostats, hence even if one of the field windings has a fault, the generator can continue to work under partial load. One disadvantage of the double claw pole machine is that it is heavier than other superconducting machine designs. This is due to the iron-cored structure. Table 1 summarises the original design of the generator.

Table 1 Double claw pole machine mass

Original generator design	
total mass	184.2 t
outer diameter	6.37 m
power output	10 MW
rotational speed	10 rpm
power density	54.28 W/kg
efficiency	94.50%

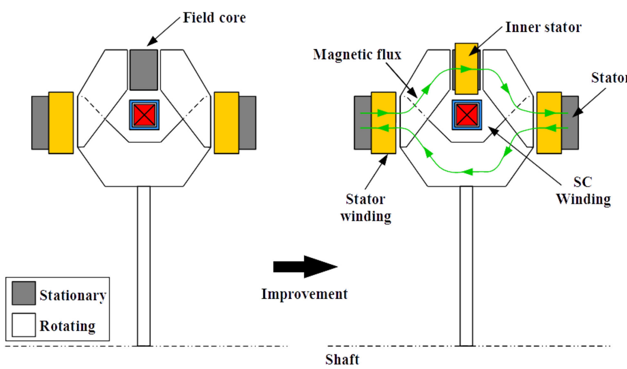

Fig. 1 *Concept of the new design*

Here, the double claw pole machine is further improved by increasing its power density. The stationary field core in between the claw poles is replaced by copper coils, creating another stator within the generator. With the added stator, the electric loading of the generator is increased and hence a higher power output can be achieved. Fig. 1 shows the transition to the new design of the double claw pole machine.

2 Methods

In order to study the double claw pole machine, a reluctance network model was developed in *MATLAB* [4]. The reluctance network is shown in Fig. 2. Each component of the machine is represented by several reluctances. Each reluctance is calculated according to its geometry and material properties using (1).

$$R = l_e/(\mu_0\mu_r A) \tag{1}$$

where l_e is the equivalent length through the component, μ_0 is the permeability of air, μ_r is the relative permeability of iron, and A is the cross-sectional area of the component. It was decided to use Vacoflux50 for the active mass due to its high saturation limit of 2.28 T at 16 kAm^{-1} [5]. In addition, all major leakage paths were considered such as leakage flux between the claw poles and zigzag leakage flux between stator teeth. A Newton–Raphson algorithm is used to solve the non-linear flux (Fig. 3).

From the reluctance network, the stator tooth flux is obtained and hence the power output can be calculated. In addition to the

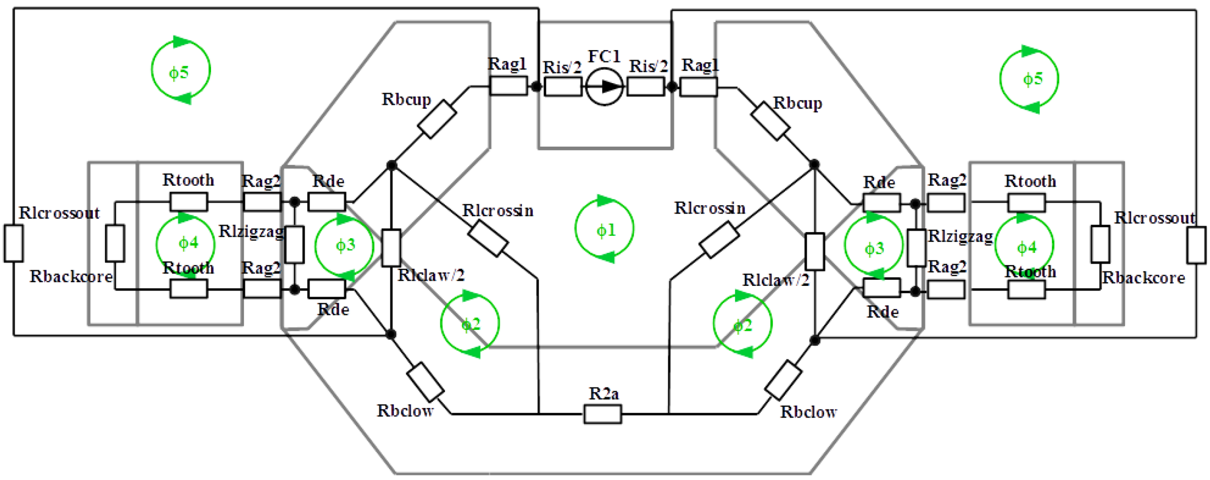

Fig. 2 *Reluctance network of the double claw pole machine*

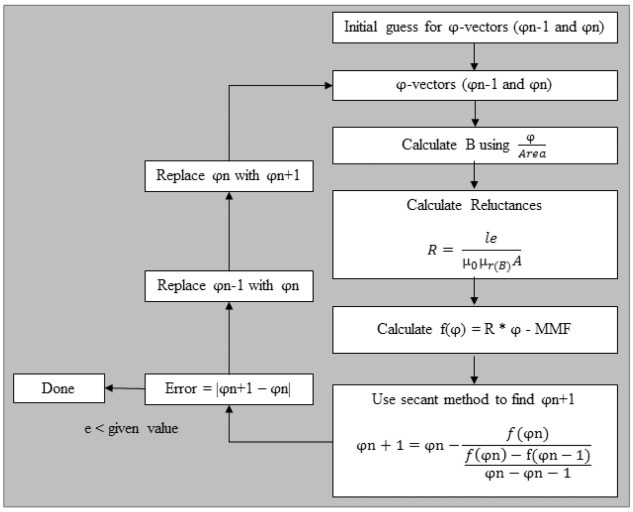

Fig. 3 *Algorithm used to solve the non-linear flux equations*

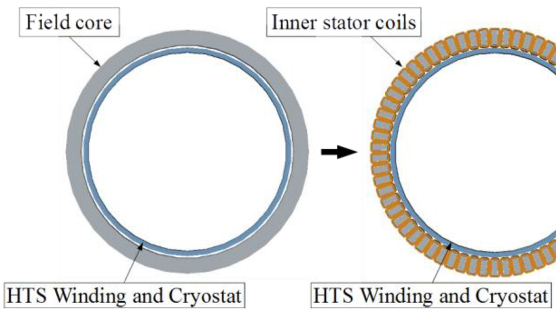

Fig. 4 *Concept for the new design*

reluctance network model, magnetostatic analysis using the simulation software *Infolytica MagNet* was performed. The finite element analysis (FEA) is used to verify the results from the reluctance network model.

Using the stator tooth flux, the power output of the stators is determined using (2).

$$P_{OUT} = N_{COIL}(E_{RMS}I_{RMS} - I_{RMS}^2 R_{COIL}) \quad (2)$$

where N_{COIL} is number of coils per stator, E_{RMS} is the induced voltage for one coil, I_{RMS} is the stator current and R_{COIL} is the resistance of a stator coil. E_{RMS} is calculated according to Faraday's law using (3).

$$E_{RMS} = (N_{TURN}\phi_{PEAK}f)/\sqrt{2} \quad (3)$$

where N_{TURN} is the number of turns per coil, ϕ_{PEAK} is the peak stator tooth flux and f is the electrical frequency. I_{RMS} is calculated using (4).

$$I_{RMS} = J_{RMS}A_{COIL} \quad (4)$$

where J_{RMS} is the current density of copper which is assumed to be 5×10^5 A/m^2 and A_{COIL} is the area of a stator coil.

3 Outcomes

From the research, it became clear that a novel design approach can be introduced to reduce the mass per kW of the machine. The field core in between the small claw poles is required in order to give support and access to the stationary superconducting field winding, it does not serve any other purpose. However, a homopolar field crosses the field core similar to the homopolar machine described in [6]. Additional power can be extracted from the generator by replacing the field core with copper coils and hence increasing the electric loading of the machine. Fig. 4 shows how the field core was modified to accommodate the new inner stator coils. The forces acting on the coils are balanced hence there is no net force acting in either direction. Similar to the C-GEN concept, the stator coils can be immersed in epoxy resin. They are then held in place by an aluminium band [7]. Similar to the outer stators, the new inner stator also consists of 66 coils. The stator teeth of the three stators are aligned with each other. This ensures that the overlapping area between the small claw poles and the stator teeth is always equal for all four air gaps.

The magnetic fields of the inner stator coils will have an effect on the performance of the superconducting tape. However, the impact on the superconducting winding is expected to be relatively small. The critical current density of superconductors mainly depends on the perpendicular flux that penetrates the tape [8]. The field produced by the coils however mainly penetrates the superconducting coils in a parallel manner. Hence, the critical current density of the superconducting tape will not be affected very strongly. Further research into the effect of the armature reaction onto the superconducting field winding is, however, required.

Fig. 5 shows the active mass of the new generator design without the structural mass.

The reluctance network model was then applied in conjunction with the new design. From the model, the peak flux for the outer stator teeth was found to be 58.1 mWb and for the inner stator teeth 74.7 mWb. Fig. 6 shows the flux variation for the outer and inner stators with the assumption made that the flux variation is sinusoidal. It can be seen that the flux variation for the inner stator is homopolar since it only varies between 0 and ϕ_{MAX}. In addition, the frequency is only half of that of the outer stators since the inner stator only sees half the number of poles.

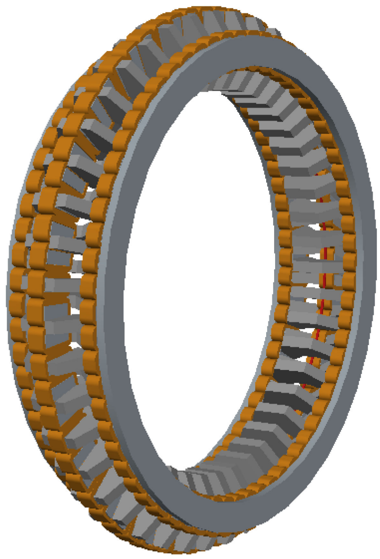

Fig. 5 *Active mass of the new generator design*

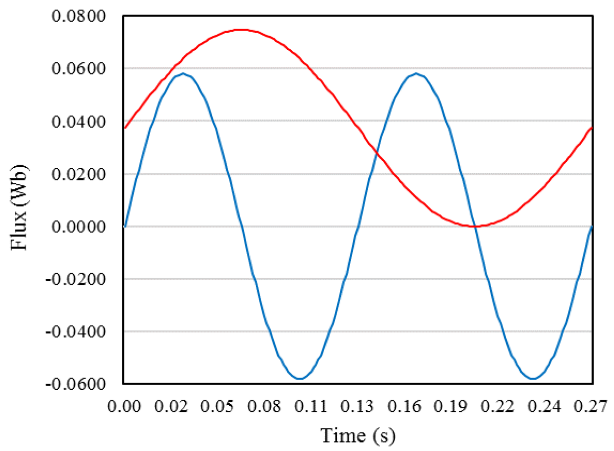

Fig. 6 *Stator tooth flux variation for the outer and inner stator*

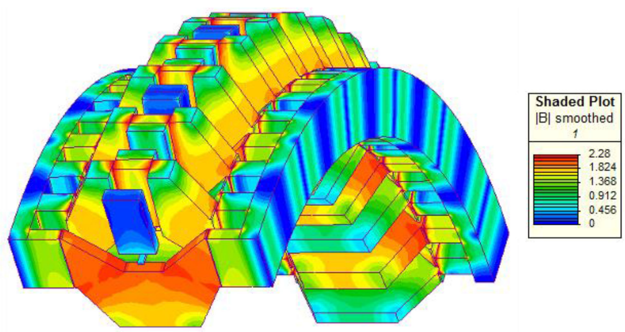

Fig. 7 *Flux density distribution for large claw poles aligned with outer stator teeth*

In order to verify the results, a 3D magnetostatic analysis using the simulation software *Infolytica MagNet* was performed. It is essential to use 3D FEA since the flux path through the machine is three-dimensional. Fig. 7 shows the magnetic flux density distribution when the large claw poles are aligned with the outer stator teeth. Fig. 8 shows the flux density distribution when the small claw poles are aligned with the inner and outer stator teeth. From the FEA results, the outer stator tooth flux density was found to be equal to 1.26 T which is equivalent to a flux of 57.7 mWb and the inner stator tooth flux density was found to be equal to 1.40 T which is equivalent to a flux of 74.2 mWb. It can be seen that there is a very good correlation between the reluctance network model and the FEA results.

Using (1)–(3), the power output was calculated to be 5 MW for each outer stator and 1.6 MW for the inner stator. Hence, an

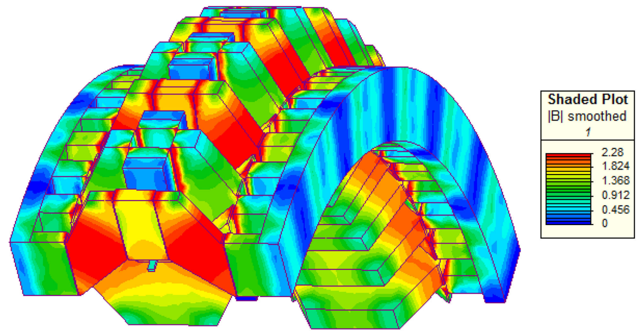

Fig. 8 *Flux density distribution for small claw poles aligned with stator teeth*

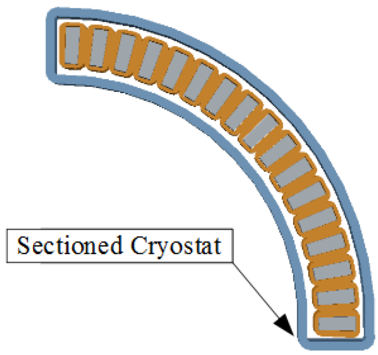

Fig. 9 *Sectioned cryostat*

Table 2 Thermal budget for generator design [3]

Thermal budget	
temperature	65 K
gas conduction (at 10^{-3} Pa)	3.4 W
suspension straps	50 W
radiation	17.4 W
current leads	48.8 W
cold-head sleeve	15.6 W
eddy current	4 W
other	15 W
total loss	**154.2 W**

additional 1.6 MW were added to the original 10 MW. Since the power generated in the inner stator is at a different frequency as compared to the outer stators, a separate power converter is required in order to extract the power.

Next to the power density, another important aspect of generators is their efficiency. The efficiency calculation of the original design of the double claw pole machine was described in detail in [3]. To calculate the efficiency, the copper losses, iron losses, cooling power, and air blowers for the armature were considered. The overall efficiency is dominated by the copper losses in the stators. The copper losses are calculated according to the dimensions of the copper wire and the number of turns. The iron losses are calculated using the Vacoflux50 datasheet and using the operating frequency in the machine, which is 7.3 Hz at 10 rpm. The cooling power required depends on the design of the cryostat. Similarly to the original design, the cryostat and superconducting field winding can be split up into several independent sections to increase the modularity of the machine. This is shown in Fig. 9.

The initial radiation heat loss was calculated to be 545 W; however, using 30 layers of multi-layer insulation (MLI) material, it was reduced down to 17.4 W. The total cooling power required was calculated to be 154.2 W. Table 2 shows the thermal budget split up into its components. Since the superconducting winding was not changed for the new design, the thermal budget remains the same as for the original generator. The required cooling power can be supplied by four 50 W cryocoolers, which allow for an

Table 3 Total losses of the 11.6 MW generator design

Total losses	
copper losses	806 kW
iron losses	6.67 kW
cryocoolers	24 kW
air blowers	50 kW
total loss	**886.67 kW**

Table 4 New generator design summarised

New generator design	
total mass	182 t
outer diameter	6.37 m
power output	11.6 MW
rotational speed	10 rpm
power density	63.54 W/kg
efficiency	92.94%

additional safety margin of 25%. The four cryocoolers have a total input power of 24 kW [9].

The copper losses were increased since an additional stator was created. The copper losses of the outer stators are equal to 510 kW. The copper losses of the inner stator can be calculated to be 296 kW. Since some of the iron in the field core was eliminated, the iron losses were reduced down to 6.67 kW.

Table 3 shows all the losses for the new generator design. As can be seen, the overall losses are dominated by the copper losses in the stators.

Hence, with the power output of 11.6 MW, the efficiency of the generator can be calculated to be equal to 92.94%. This is slightly lower than the original generator design, which has an efficiency of 94.5%.

The parameters of the new generator design are highlighted in Table 4. The total mass of the generator is lighter since some of the iron in the field core was eliminated. The generator still has the same outer diameter as for the original design. With the new power output and the new mass, the power density of the generator was increased from 54.28 to 63.54 W/kg.

4 Conclusion

Higher power density generators are needed in order to lower the cost of energy of large direct-drive wind turbines. The double claw pole machine was introduced as a promising option for this objective. However, it was found to be still too heavy to satisfy the future needs of the wind energy industry. To further increase the power density of the double claw pole machine, a new design approach was introduced. The stationary field core was replaced by iron-cored copper coils to create another stator. A reluctance model was developed to verify the design in conjunction with a FEA to verify the results. It was shown that an additional 1.6 MW to the original 10 MW can be gained with the new design, increasing the power density from 54.28 to 63.54 W/kg, while maintaining the same machine diameter.

5 Acknowledgments

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